ON TERRESTRIAL MICROWAVE RADIATION DATA OBTAINED WITH SATELLITES

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AJAY PRAKASH

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DECLARATION

This is to certify that the work presented in this thesis has been carried out by the candidate under my supervision in the Department of Physics, Indian Institute of Technology, Kanpur, India.

To the best of the candidate's knowledge this work is original and has not formed the basis for the award of any other degree.

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AJAY PRAKASH

CONTENTS

ABSTRACT

The work presented in this thesis mainly deals with the sea-surface effects in satellite microwave radiation measurements.

The earth receives nearly all its energy from the sun in form of electromagnetic radiation, the bulk of it being below 0.4 μm. A redistribution of this energy takes place due to the earth-atmosphere systems, which reradiates in the long wave length (mm and cm) region. The satellite 'BHASKAR' observes this microwave radiation at two different frequencies viz. 22.235 GHz and 19.35 GHz by radiometers on board, and scales it in terms of brightness temperatures.

The contribution towards the total brightness temperatures comes from (i) earth emission attenuated by atmosphere (ii) self attenuated atmospheric emission (iii) reflected part of the downward atmospheric emission. An attempt has been made to study these brightness temperatures at the above mentioned frequencies and their dependences on various surface and atmospheric parameters has been estimated. Lastly, as a preliminary result, the total brightness temperature has been written empirically in terms of the most sensitive parameters, upon which it depends.

CHAPTER 1

INTRODUCTION

The earth receives virtually all its energy from space in the form of solar electromagnetic radiation. The mean temperature of the earth does not vary significantly over time periods of the order of centuries, indicating a reasonably close over all balance between the absorbed solar radiation and the diffuse stream of low temperature thermal radiation emitted by the planet.

The irradiation at mean solar distance know as the solar constant, is approximately 2 Cal./cm^2/min., providing a mean flux of about 0.5 Cal./cm^2/min., the factor 4 being the ratio of the surface area to the cross-section of a sphere. Of this, approximately 40 % is reflected back, and the rest i.e. 0.3 Cal./cm^2/min. is absorbed by the earth's atmosphere.

This energy is radiated back into space as long wavelength thermal radiation. Assuming earth to radiate as a black body in the infra red spectrum. We can compute the general level of terrestrial temperatures. The energy absorbed by the earth can be written as

$$\text{absorbed energy} = S \pi r^2 (1 - a) \qquad (1,1)$$

where S = solar constant = 2 Cal./cm^2/min.

r = radius of earth

a = albedo for solar radiation = 0.4.

The energy emitted by the earth is

$$\text{emitted energy} = 4\pi r^2 \sigma \Theta_e^4 \qquad (1.2)$$

where σ = Stefan-Boltzman constant

Θ_e = Equivalent emission temperature of earth.

If the planet is in steady state, we may equate (1.1) and (1.2) obtaining a value of 246.5 ^oK for Θ_e. The computed temperature is lower than the average for the earth's surface, but is close to the average temperature of the atmosphere itself, indicating that a considerable fraction of the terrestrial radiation comes from the atmosphere and not from the surface.

Assuming the sun and the earth to be black bodies at 6000 ^oK and 246.5 ^oK respectively, the spectral intensity B_{T} is given by the Planck's formula

$$B_{\lambda T} = \frac{2hc^2\pi}{\lambda^5} \frac{1}{[e^{hc/\lambda kT} - 1]} \qquad (1.3)$$

and is shown in fig. (1.1).

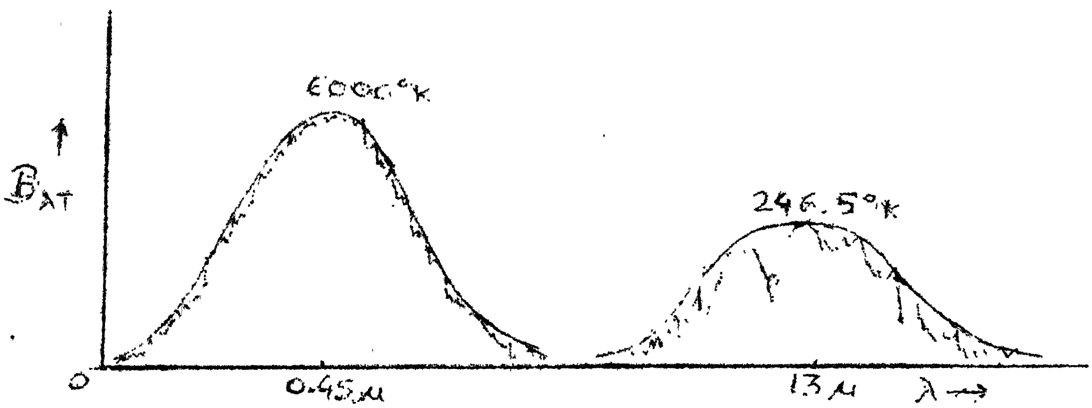


Fig. 1.1. Black body curves for 6000 ^oK and 245 ^oK. The lines below show the departure from black body spectrum.

It may be noted that the solar flux lies entirely below a wavelength of about 4μ and the terrestial flux entirely above it. It is therefore, possible to treat the terrestrial and solar fluxes separately.

Of course, the actual spectrum of the solar as well as terrestrial radiation is not exactly the black body spectrum. In the case of terrestrial radiation the terrestrial surface emitts its own characteristic radiation depending upon the nature and the temperature of the surface in various geographical regions. This radiation is further modified by the atmospheric constituents. The final spectrum is schematically shown in fig. (1.1). It is the departure from the black body spectrum which provides information about the state of the atmosphere and the surface of the earth. This is analogous to learning about the solar structure from Fraunhoffer lines.

The surface emission, assumed to be governed by Kirchoff's law, is given by

$$I_\lambda = \varepsilon_\lambda B_{\lambda T} \tag{1.4}$$

where ε_λ is the emissivity which depends upon the nature of the surface. In the atmosphere the principal constituents are O_2, N_2, A which are almost transparent to wavelengths greater than 4μ but minor polyatomic constituents such as H_2O, CO_2, O_3 etc. have intense and complex absorption spectra and are present in sufficient quantities to absorb a good portion of the terrestrial radiation. Dust, haze and particularly

clouds (condensed water) absorb strongly almost throughout the infra-red spectra. The general absorption characteristics are shown in figure 1.2.

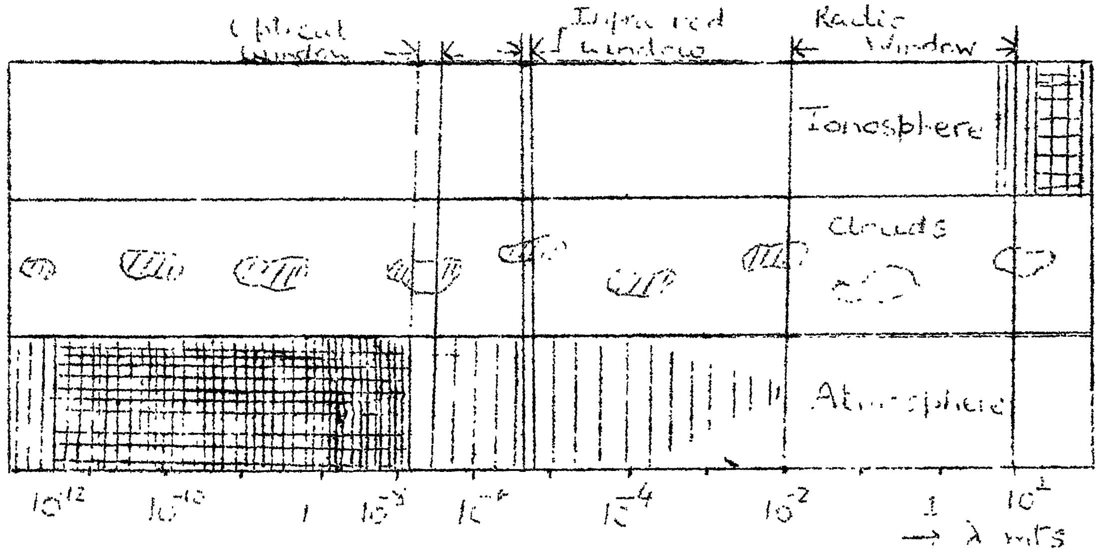


Fig. 1.2. General absorption characteristic of the atmosphere.

The use of artificial earth satellites[7] in the seventees has changed the content and greatly increased the volume of information about the terrestrial radiation. In this, the visible and infra-red spectra regions have been studied more extensively. Much can also be learnt from the longer mm and cm waves (microwaves).

There are some advantages in carrying out microwave radiation measurements.

(i) In the microwave region the absorption is due to rotational transitions in H_2O and O_2 molecules.in the atmosphere and the spectral lines are reasonably well separated. Therefore, one can choose to look at a resonance frequency

or at an off resonance frequency to stress either the atmospheric effect or the ground effect in radiation.

(ii) The absorption coefficients at these separate resonant frequencies can be calculated more easily from first principles. In the infra-red region, on the other hand, there are overlapping lines forming bands and appropriate band models have to be used to obtain the absorption coefficients.

(iii) Clouds (condensed water) are opaque to infra red radiation starting from the ground but they are reasonably transparent in the microwave region. One can, therefore, study the surface of the earth even in cloudy weather, which is important, since the cloud cover is over about 60 % of the terrestrial surface. The structure of the clouds themselves can be studied.

Considering that the terrestrial spectrum peaks at about 13 μm, one would expect very small intensities at the tail end of the Planck's distribution around a cm. It is true that the black body intensity decreases as one goes from $\lambda = 10$ μm to 1 cm but the minimum perceptible power for a microwave receiver is lower by a factor 10^9 compared to infra-red receivers. The lower level of the microwave signal can therefore readily be coped with.

However, there is a disadvantage in going to microwave region keeping in view the angular resolution. By Rayleigh criterion the minimum angle of resolution is given by

$$\beta \simeq 1.22 \frac{\lambda}{D} \tag{1.5}$$

where D is the size of the antenna. As increases from μm to cm region, it is necessary to increase the antenna size to keep the value of β low.

On June 7, 1979, the satellite 'Bhaskar' of the Indian Space Research Organization was launched from a Russian cosmodrome with a Russian rocket. The satellite which orbits at a mean height of 525 kms carries 3 microwave radiometers, two of them are tuned at 19.35 GHz and one at 22.235 GHz, which is at the resonance frequencies for rotational transitions in water (vapour) molecule. The radiometer measures intensity in terms of the brightness temperature T_B is given by

$$T_B = \frac{c^2}{2\nu^2 K} I_\nu \tag{1.6}$$

K being the Boltzman constant.

The temperature resolution of the radiometers is 1 ^oK. The radiation gathering horns percieves a circle of 150 km diameter at 19.35 GJz and 200 km diameter at 22.235 GHz. The brightness temperature data is gathered whenever the satellite appears above the day horizon at Ahmedabad and Sri Harikota Space Centres and is transmitted to these stations. A typical sequence of data gathered is shown in figure 1.3.

The intensity measured by the satellite can be conveniently divided into three components as shown in fig. 1.4. $T_B(I)$ is the surface emission attenuated by the atmosphere. $T_B(II)$ is the self attenuated atmospheric emission and $T_B(III)$

is the reflected part of the downward atmospheric emission. The net brightness temperature is therefore given by

$$T_B = T_B(I) + T_B(II) + T_B(III) \qquad (1.7)$$

In the present project we have developed a computer programme to calculate $T_B(I)$, $T_B(II)$ and $T_B(III)$ and thus connect the observed brightness temperatures with the characteristic parameters of the atmosphere and surface in cloudless skies. In the limited time available for this project, in the one year M.Phil. programme, we could use it only for a couple of applications. We have firstly tried to estimate the relative contributions of the surface and of the atmosphere over land and oceans. Secondly we have estimated the sensitivity of the brightness temperature to the variations in various parameters. Finally, we have attempted to express the brightness temperature empirically involving some linear terms for ready calculations, without a computer programme.

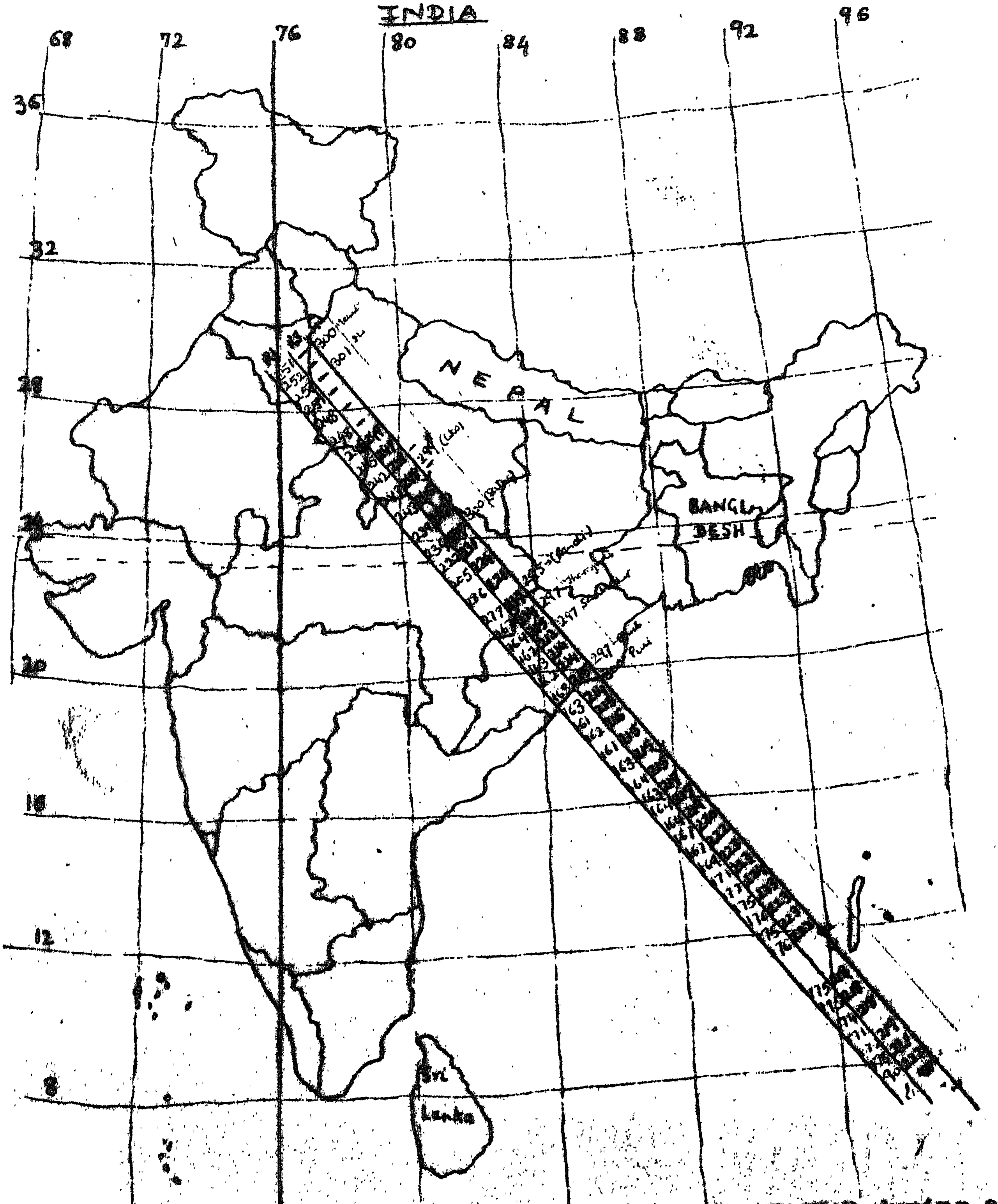
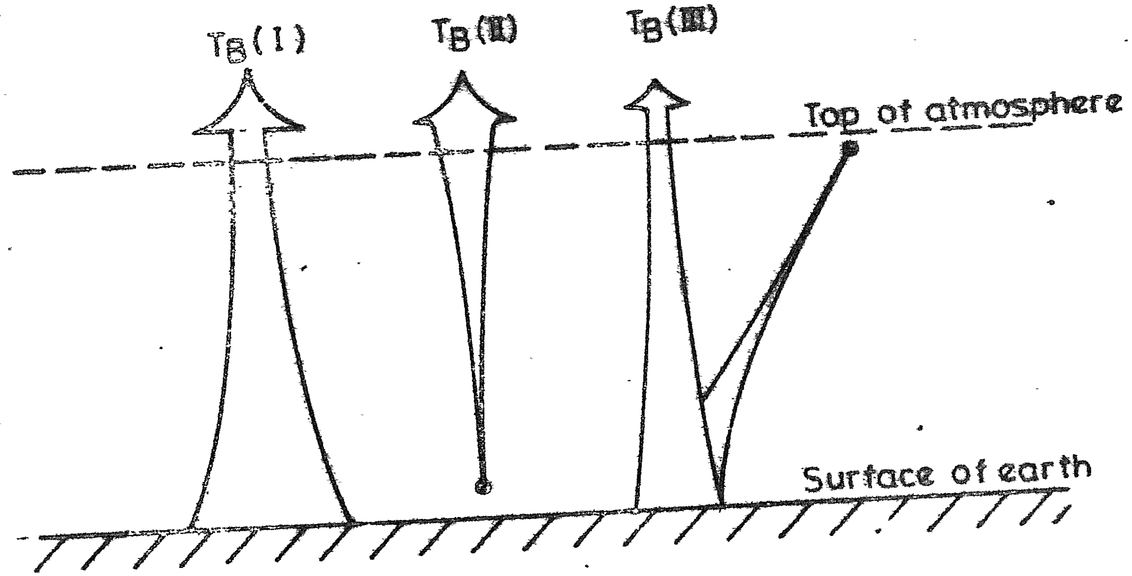


Fig 1.3. A typical sequence of data taken by BHASKAR during orbit no 1327, on Sept. 3, 1979. The upper line shows the path of the beam centre while the columns R1 and R3 show the brightness temp. recorded by radiometers 1 and 3 respectively.



$$T_B = T_B(I) + T_B(II) + T_B(III)$$

Fig. 1.4 A schematic diagram showing the various contribution towards the total brightness temperature as " seen" by the satellite.

CHAPTER 2

RADIATIVE PROCESS

In this chapter we intend to discuss some important relations, useful in the study of terrestrial radiation.

2.1 Intensity and Flux

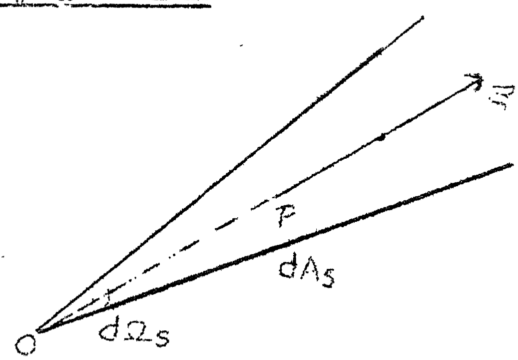


Fig. 2.1. A Cone presenting area dA_S perpendicular to the direction of radiation beam.

Consider a point P in the radiation field. Let S be a direction defining vector through P. Let dA_s be an element of area with S as normal. Consider a cone with vertex angle $d\Omega_s$ circumscribing area dA_s as shown.

Let d^4E_ν be the radiative energy in the frequency interval ν to $\nu + d\nu$ passing through dA_s per unit time and confined to the cone. Then the intensity of radiation $I_\nu(\vec{S})$ at P in the direction $\vec{S}$ is defined by

$$I_\nu(\vec{S}) = \frac{d^4E_\nu}{d\nu\, dt\, dA_s\, d\Omega_s} \qquad (2.1)$$

However, if the direction of S and the element of area dA_R are not same as in fig. 2.2 then the energy $d^4E'_\nu$ passing

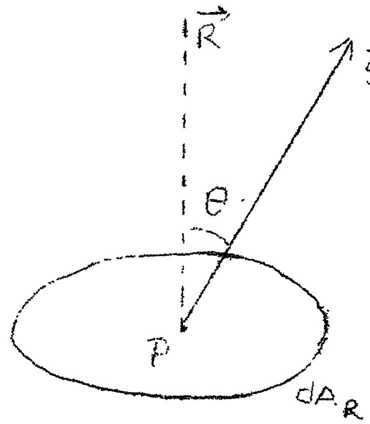


Fig. 2.2. The element area dA_R makes an angle with the direction of incident radiation.

through dA_R due to the radiant beam along $\vec{S}$ is

$$d^4E'_\nu \quad = \quad I_\nu(\vec{S})\; d\nu\, dt\; dA_R\; \cos\theta\; d\Omega \qquad (2.2)$$

$dA_R . \cos\Theta$ being projection of dA_R in the direction $\vec{S}$.

The total radient energy passing through dA_R from one hemisphere to other is

$$= \quad d\nu\, dt\; dA_R \int_{\text{hemisphere}} I_\nu(\vec{S})\; \cos\theta\; d\Omega$$

Flux is such energy passing per unit values of $d\nu$, dt and dA_R, and therefore

$$F_R \quad = \int_{\text{hemisphere}} I_\nu(\vec{S})\; \cos\theta\; d\Omega \qquad (2.3)$$

2.2 Interaction of Radiation with Matter

The energy d^4E_ν passing through A_s passes through $A_{s'}$ after a time ds/C. If however, matter is present in the volume bounded by A_s, $A_{s'}$ then the energy $d^4E'_\nu$ passing through

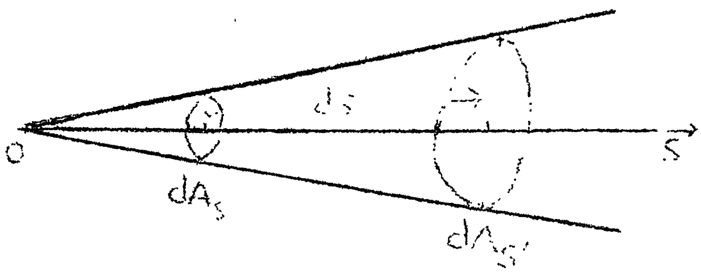


Fig. 2.3. The active volume between dA_s and $dA_{s'}$ contains matter which leads to extinction of the radiation beam.

$dA_{s'}$ may not be equal to d^4E_ν due to the processes of absorption, emission, scattering out and scattering in, to the cone. We assume that the rates of these processes are proportional to the mass of the matter contained in the active volume and further that the rate of absorption and scattering out is proportional to the intensity of radiation. We therefore have

$$\begin{aligned} d^5E_\nu &= d^4E'_\nu - d^4E_\nu \\ &= [I_\nu(S + ds) - I_\nu(S)]\, d\nu\, dt\, dA\, d\Omega \\ &= dI_\nu\, d\nu\, dt\, dA\, d\Omega \end{aligned}$$

and

$$dI_\nu = dI_\nu^{ab} + dI_\nu^{em} + dI_\nu^{ScO} + dI_\nu^{ScI} \qquad (2.4)$$

where

$$\begin{aligned} dI_\nu^{ab} &= -\hat{\alpha}_\nu I_\nu \rho\, ds \\ dI_\nu^{em} &= \hat{\beta}_\nu \rho\, ds \qquad (2.5) \\ dI_\nu^{ScO} &= \hat{\sigma}_\nu I_\nu \rho\, ds \\ dI_\nu^{ScI} &= \rho\, ds\, \hat{\sigma}_\nu \int I_\nu(\vec{S})\, \Psi(\Omega_{s'}, \Omega_s)\, d\Omega_{s'} \end{aligned}$$

where $\hat{\alpha}_\nu$, $\hat{\sigma}_\nu$ are respectively called the mass absorption and

mass scattering coefficients, and ψ is the scattering distribution function.

We define $\alpha_\nu = \hat{\alpha}_\nu \rho$ and $\sigma_\nu = \hat{\sigma}_\nu \rho$ as the volume absorption coefficients and $\beta_\nu = \hat{\beta}_\nu \rho$ will be discussed shortly. Therefore

$$\frac{dI_\nu}{ds} = (-\alpha_\nu + \sigma_\nu) I_\nu + \beta_\nu + \sigma_\nu \int I_\nu(S') \psi(\Omega_{s'}, \Omega_s) d\Omega_{s'} \qquad \ldots\ldots (2.6)$$

2.3 Matter and Radiation in Equilibrium

The properties of radiation in thermodynamic equilibrium as in a constant temperature enclosure were first studied by Kirchoff in 1882 and important contributions were made by Planck in 1905.

The implications of the equilibrium condition are far reaching. They are :

(i) the radiation in thermodynamic equilibrium with matter is homogeneous, unpolarised and isotropic, which implies $dI_\nu = 0$

(ii) since the temperature of matter is constant in time hence $(dI_\nu^{ab} + dI_\nu^{em}) = 0$. Therefore $dI_\nu^{ScO} + dI_\nu^{ScI} = 0$ i.e. the scattering out is balanced by the scattering in.

(iii) $$I_\nu = \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/kT} - 1} = B_{\nu T} \qquad (2.7)$$

since

$$\alpha_\nu I_\nu \, ds = \beta_\nu \, ds$$

or $$\beta_\nu = \alpha_\nu B_{\nu T} \qquad (2.8)$$

Therefore in equilibrium state

$$\frac{dI_\nu}{ds} = 0, \quad dI_\nu^{ab} = -\alpha_\nu I_\nu \, ds, \quad dI_\nu^{em} = -\alpha_\nu B_{\nu T} \, ds,$$

$$dI_\nu^{ScO} = -dI_\nu^{ScI}$$

where $I_\nu = B_{\nu T}$

2.4 Non-equilibrium State

In the non-equilibrium state, as in the case of atmosphere $\frac{dI_\nu}{ds} \neq 0$ and $I_\nu \neq B_{\nu T}$. It is, however, assumed here that $dI_\nu^{em} = -\alpha_\nu B_{\nu T}$ and $(dI_\nu^{ScO} + dI_\nu^{ScI})$ is negligible.

Thus

$$-\frac{1}{\alpha_\nu}\frac{dI_\nu}{ds} = (I_\nu - B_{\nu T}) \qquad (2.9)$$

which is the equation of radiative transfer.

The first assumption viz. $dI_\nu^{em} = -\alpha_\nu B_{\nu T}$ implies that the emissive property of matter is same inside and outside an equilibrium enclosure. This cannot be strictly valid due to the process of induced emission. However, calculations show that this approximation is reasonably good for the conditions existing in the atmosphere. The second assumption viz. $(dI_\nu^{ScO} + dI_\nu^{ScI}) = 0$ really amounts to neglecting scattering processes. Unlike for the visible region, the scattering cross section, for the infra red and particularly for microwaves, is expected to be small except in the presence of rain drops.

2.5 Solution of the Equation of Radiative Transfer

The equation (2.9) has the solution

$$I_\nu(S_o) = I_\nu(0)\, e^{-\int_0^{S_o} \alpha_\nu(S)\, ds} + \int_0^{\infty} ds\, \alpha_\nu(S)\, B_{\nu T}(S)\, e^{-\int_S^{S_o} \alpha_\nu(S')\, ds'} \quad \ldots. \; (2.10)$$

where $I_\nu(0) = I_{\nu G} + I_{\nu R}$

$I_{\nu G}$ being the intensity of upward ground emission at the surface and $I_{\nu R}$ is the intensity of the reflected part of the downward atmospheric emission.

Now, if T_G is the ground temperature, then $I_{\nu G} = \varepsilon\, B_{\nu T_G}$ following from the definition of emissivity ε. What remains now is to write an expression for I_R.

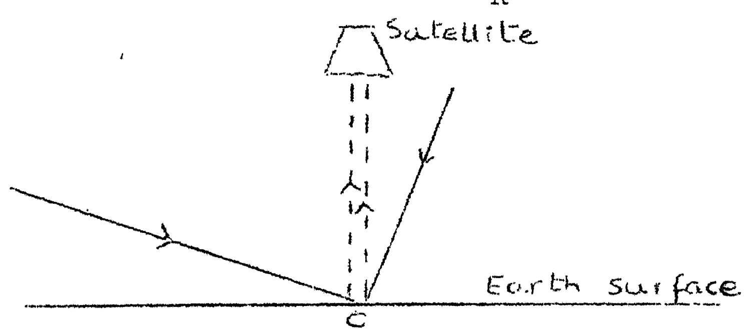


Fig. 2.4. Non-specular reflection from earths surface contributes to build up I_R.

Assuming that the satellite is looking vertically downward so that $ds = dz$ where $s = 0$ corresponds to the ground level. The reflection from the surface is not necessarily specular and therefore several downward rays contribute to the intensity of the reflected vertical ray. In this situation it is necessary to consider the reflection distribution function[3] defined as follows.

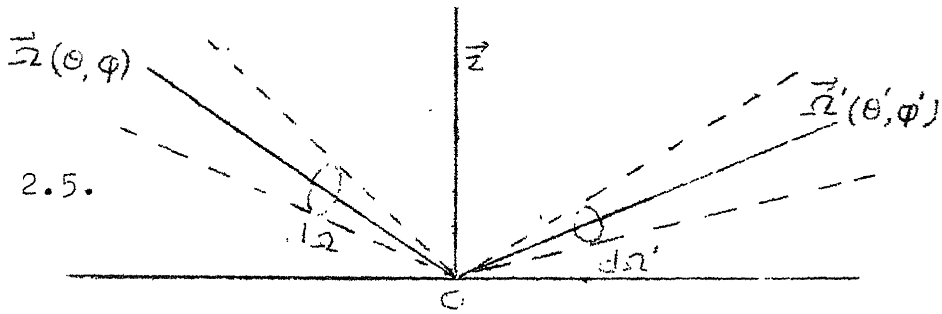


Fig. 2.5.

Let $\vec{\Omega} = (\theta, \varphi)$ and $\vec{\Omega}' = (\theta', \varphi')$ denote two directions. If $I_\nu(\vec{\Omega})$ is the intensity of the incident beam confined to a cone with solid angle $d\Omega$, then the intensity of the beam reflected in the direction $\vec{\Omega}'$ is given by

$$dI_\nu(\vec{\Omega}') = r_\nu(\vec{\Omega},\vec{\Omega}')\, I_\nu(\vec{\Omega}) \cos\theta \, d\Omega \tag{2.11}$$

The net intensity of the beam reflected in the direction $\vec{\Omega}'$ due to incident beams from different directions $\vec{\Omega}$ is then given by

$$I_\nu(\vec{\Omega}') = \int_{\Omega=2\pi} r_\nu(\vec{\Omega},\vec{\Omega}')\, I_\nu(\vec{\Omega}) \cos\theta \, d\Omega \tag{2.12}$$

In our case, the direction $\vec{\Omega}'$ is characterised by $\theta = \varphi = 0$ and the intensity of the incident beam $I_\nu(\vec{\Omega})$ from the direction $\vec{\Omega}$ is given by

$$I_\nu(\vec{\Omega}) = \int_0^\infty dz \sec\theta \, \alpha_\nu(z)\, B_{\nu T}(z)\, e^{-\int_0^z \alpha(z') \sec\theta \, dz'} \tag{2.13}$$

This expression is written in analogy of the second term of the expression (2.10). Substitution of (2.13) in (2.12) gives the required reflected intensity $I_{\nu R}$. We therefore have from (2.10)

$$I_\nu(\infty) = \varepsilon_\nu B_{\nu T_G} e^{-\int_0^\infty \alpha_\nu(z)\, dz}$$

— Continued

$$+ \int_0^{\infty} dz \; \alpha_\nu(z) \; B_{\nu T}(z) \; e^{-\int_0^z \alpha(z')dz'}$$

$$+ \int_{\Omega=2\pi} d\Omega \cos\theta \; r_\nu(\vec{\Omega},\vec{\Omega}') \left\{ \int_0^{\infty} dz \sec\theta \; \alpha_\nu(z) \; B_{\nu T}(z) \right.$$

$$\left. \times \; e^{-\int_z^{\infty} \alpha_\nu(z') \sec\theta \, dz'} \right\} e^{-\int_0^{\infty} \alpha_\nu(z) dz} \qquad (2.14)$$

The replacement $ds = dz \sec\theta$ is valid for a flat surface where the curvature of the earth's surface in neglected. When it is taken into account we must write

$$ds = \frac{1 + \frac{z}{R}}{\left\{\cos^2\theta + \frac{2z}{R} + \frac{z^2}{R^2}\right\}^{1/2}} \quad dz \qquad (2.15)$$

where R is the radius of the earth.

In the long wavelength (Rayleigh-Jean) limit the function $B_{\nu T}$ can be well approximated by the expression

$$B_{\nu T} = \frac{2\nu^2}{c^2} \; k\,T \qquad (2.16)$$

which is applicable for the microwave radiation from the earth. It is then convenient to express all intensities in terms of brightness temperatures defined by

$$I_\nu = \frac{2\nu^2}{c^2} \; k\,T \qquad (2.17)$$

Thereby, expression (2.14) can be written in terms of temperatures T and brightness temperature TB as

$$TB(\infty) = \varepsilon_\nu \; T_G \; e^{-\int_0^{\infty} \alpha_\nu(z) \; dz}$$

$$+ \int_0^{\infty} dz\ \alpha_\nu(z)\ T(z)\ e^{-\int_z^{\infty} \alpha_\nu(z')\, dz'}$$

$$+ \int_{\Omega=2\pi} d\Omega \cos\theta\, r(\vec{\Omega},\vec{\Omega}') \left\{ \int_0^{\infty} dz\ \sec\theta\ \alpha_\nu(z) T(z) e^{-\int_0^z \alpha(z')\sec\theta\, dz'} \right\}$$

$$\times\ e^{-\int_0^{\infty} \alpha_\nu(z)\, dz} \qquad (2.18)$$

$$= \mathrm{TB(I)} + \mathrm{TB(II)} + \mathrm{TB(III)}$$

In order to calculate the brightness temperature $TB(\infty)$ we must therefore know the following quantities

ε_ν , T_G, $\alpha_\nu(z)$, $T(z)$ and $r(\vec{\Omega},\vec{\Omega}')$

2.6 Absorption Coefficient $\alpha_\nu(z)$

The water molecule undergoes a rotational transition at ν = 22.235 GHz. The absorption coefficient in the neighbourhood of this frequency has been calculated by Van Vleck[1] and is given by

$$\alpha_\nu = \alpha^R + \alpha^{NR}$$

$$= \left[\frac{C_1\, e^{-644/T}}{T^{5/2}}\, \nu^2 \Delta\nu \left\{ \frac{1}{(\nu-\nu_0)^2 + \Delta\nu^2} + \frac{1}{(\nu+\nu_0)^2 + \Delta\nu^2} \right\} \right.$$

$$\left. + \ C_2\, T^{-3/2}\, \nu^2 \Delta\nu \right]$$

where $\Delta\nu = C_3\ (P/P_0)\ (\frac{T}{318})^{-5/8}\ (1 + 4.6\times10^{-3}\rho_v)$ GHz (2.19)

and ν_0 = 22.235 GHz.

and $C_1 = 3.507\text{x}10^2$ $C_2 = 25.384\text{x}10^{-4}$ $C_3 = 2.62$

α_ν is measured in km^{-1}.

Here α_ν^R is the resonant contribution and α_ν^{NR} is the non-resonant contribution arising from the tails of distant resonances. It has been recognized experimentally that the theoretical coefficient of the non-resonant term has to be multiplied by a factor of 5 to obtain α_ν in agreement with the experimental values. This has been taken into account in writing equation (2.19).

The absorption coefficient is thus a function $\alpha_\nu(T, p/p_o, \rho_v)$, i.e. of temperature T, pressure ratio p/p_o and vapour density ρ_v at the height z where α_ν is required. In the hydrostatic approximation, temperature distribution T(z) determines the pressure ratio p/p_o, since

$$(p/p_o) = \exp\left\{ -g/R \int_0^z \frac{dz'}{T(z')} \right\} \tag{2.20}$$

To find $\alpha_\nu(z)$ we must therefore know the distribution T(z) of temperature and $\rho_v(z)$ of the vapour. The data obtained by radiosondes provides these distributions. Alternately, models can be used. In this work, the following has be assumed

$$T(z) = T(0) - \gamma z \tag{2.21}$$

$$\rho_v(z) = \rho_v(0)\ e^{-k\ z} \tag{2.22}$$

with the above expression for $\rho_v(z)$ the total water content W in the atmosphere is given by

$$W = \int_0^\infty \rho_v(z)\ dz = \rho_v(0)/K \tag{2.23}$$

2.7 Emissivity and the Reflection Distribution Function

The emissivity ε_ν and the reflection distribution function $r_\nu(\vec{\Omega},\vec{\Omega}')$ are characteristic properties of the surface.[4]

If a beam is incident in the direction $\vec{\Omega}$ and is confined to a cone $d\Omega$, the energy incident per unit intervals of ν, t and A (area) is $I_\nu(\vec{\Omega}) \cos\theta \, d\Omega$. Again if R_ν is the fraction reflected, a_ν is the fraction absorbed and t_ν is the fraction transmitted, we must have

$$R_\nu + a_\nu + t_\nu = 1 \tag{2.24}$$

For an opaque body we have $t_\nu = 0$. It is assumed that $a_\nu = \varepsilon_\nu$, the emissivity. Therefore we have

$$R_\nu = 1 - \varepsilon_\nu \tag{2.25}$$

With the incident intensity $I(\vec{\Omega})$, the reflected intensity in the direction $\vec{\Omega}'$ is given by

$$I(\vec{\Omega}') = r_\nu(\vec{\Omega},\vec{\Omega}') \, I(\vec{\Omega}) \cos\theta \, d\Omega$$

and the reflected energy can be written as

$$I(\vec{\Omega}') \cos\theta' \, d\vec{\Omega}' = r_\nu(\vec{\Omega},\vec{\Omega}') \, I(\Omega) \cos\theta \, d\Omega \cos\theta' \, d\Omega'$$

Therefore the total reflected energy is given by

$$\int_{\Omega'=2\pi} I(\vec{\Omega}') \cos\theta' \, d\Omega' = I(\Omega) \cos\theta \, d\Omega \int_{\Omega=2\pi} r_\nu(\vec{\Omega},\vec{\Omega}') \cos\theta' \, d\Omega'$$

The fraction R_ν of the incident energy which is reflected is therefore given by

$$R_\nu = \frac{I(\Omega)\cos\theta\, d\Omega \int_{\Omega'} r(\vec{\Omega},\vec{\Omega}')\cos\theta'\, d\Omega'}{I(\Omega)\cos\theta\, d\Omega}$$

$$= \int_{\Omega'=2\pi} r_\nu(\vec{\Omega},\vec{\Omega}')\cos\theta'\, d\Omega'$$

Since the reflection distribution function is symmetric i.e. $r(\vec{\Omega},\vec{\Omega}') = r(\vec{\Omega}',\vec{\Omega})$ we have

$$R_\nu = \int_{\Omega'=2\pi} r_\nu(\vec{\Omega}',\vec{\Omega})\cos\theta'\, d\Omega'$$

Interchanging Ω and Ω' we have

$$R_\nu = (1 - \varepsilon) = \int_{\Omega=2\pi} r_\nu(\vec{\Omega},\vec{\Omega}')\cos\theta\, d\Omega \qquad (2.26)$$

The emissivity ε_ν and $r_\nu(\vec{\Omega},\vec{\Omega}')$ are thus related by eq. (2.26).

According to equation (2.18) we have

$$TB(III) = \int_{\Omega=2\pi} d\Omega\cos\theta\, r_\nu(\vec{\Omega},\vec{\Omega}')\left\{\int_0^\infty dz\, \alpha_\nu(z)\sec\theta\, T(z)\, e^{-\int_0^z \alpha(z')\sec\theta\, dz'}\right\} e^{-\int_0^\infty \alpha_\nu(z)\, dz} \qquad (2.27)$$

This term can thus be calculated if the function $r(\vec{\Omega},\vec{\Omega}')$ is known.

The function $r(\vec{\Omega},\vec{\Omega}')$ has been calculated by Shifrin et al. for sea water. Land masses are however much less uniform from region to region and the function $r(\vec{\Omega},\vec{\Omega}')$ is not available. It is necessary then to attempt to eliminate $r(\vec{\Omega},\vec{\Omega}')$ from (2.27) by using (2.26). So that the number of parameters characteristic of land are reduced to two, namely T_G and ε_ν. This has been

attempted and discussed is the next chapter.

It is therefore possible to calculate the brightness temperature TB if the following parameters are known.

ν, ε_{ν}, T_G, T_O, γ, K, W.

CHAPTER 3

CALCULATIONS AND RESULTS

3.1 Calculations

To carry out the calculations a computer programme, to calculate the absorption coefficient α_ν and the brightness temperatures TB(I), TB(II) and TB(III), was developed. For the calculation of α_ν as given by eq. 2.19, the input parameters required are T_0, γ, K and W. Average values of these parameters during the winter months over New Delhi were used(6), to obtain α as a function of frequency (fig. 3.1) and α_ν as a function of height z (fig. 3.2).

As seen in fig. 3.1 the curve α vs ν is assymetric due to the non-resonant term. As a function of z, α_ν decreases approximately exponentially. The values of α obtained agree well with those calculated by Rabinovich and Shchukin.

For calculation of TB(I) and TB(II) the input parameters are $\alpha_\nu(z)$, ε_ν, ν, T_G and γ. These temperatures were calculated using equation 2.18. However, the estimation of TB(III) is not so straightforward and requires a brief discussion. TB(III) is given by

$$\mathrm{TB(III)} = \int_{\Omega=2\pi} d\Omega \cos\theta \, r(\vec{\Omega},\vec{\Omega}') \left\{ \int_0^\infty dz \, T(z) \, \alpha_\nu \sec\theta \, e^{-\int_0^z \alpha \sec\theta dz} \right\} \times e^{-\int_0^\infty \alpha_\nu dz}$$

$$= \int_{\Omega=2\pi} d\Omega \cos\theta \, r(\vec{\Omega},\vec{\Omega}') \; \mathrm{TD}(\theta) \; e^{-\int_0^\infty \alpha_\nu dz} \qquad (3.1)$$

where TD(Θ) is the brightness temperature of the downward atmospheric emission approaching at an angle Θ. This temperature TD as a function of Θ is plotted in fig. 3.3. Further, we rewrite 3.1 as

$$TB(III) = \left\{ \int_0^{2\pi} d\varphi \int_0^{\pi/2} d\theta \sin 2\theta \, r_\nu(\vec{\Omega}, \vec{\Omega}') \, TD(\Theta) \right\} e^{-\int_0^\infty \alpha_\nu dz} \qquad \ldots\ldots\ldots \quad (3.2)$$

The integrand in the above equation 3.2 is a product of r_ν, T(Θ) and sin 2θ, which are also shown in fig. 3.3. The values of r_ν used were taken as calculated by Shifrin and Ionina( ) over sea.

We note that the function r_ν is negligibly small for angles $\Theta > 45^\circ$ i.e. downwards rays incident at an angle larger than 45° do not contribute significantly towards vertical reflection. The temperatures TD rise rapidly for angles above 45°, and in this region the curvature effect due to earth is noticeable. However, since r_ν vanishes in this region, it is not necessary to introduce the curvature effect as given by eq. 2.15. Rabinovich and Shchukin(2) have calculated TB for meteorological conditions prevailing in summer over the Caspian Sea. We got identical results when we used their input parameters.

Over land the distribution function $r_\nu(\vec{\Omega}, \vec{\Omega}')$ is not known. We have assumed here that the reflection distribution function would continue to be negligible beyond 45°, and then replaced the function TD(θ) by its average value so that

$$TB(III) = \overline{TD(\theta)} \, [1 - \varepsilon_\nu] \qquad (3.3)$$

3.2 Results

At Space Applications Centre, Ahmedabad a working group was interested in finding the wind velocity over Oceanic surface by using the brightness temperature data at 19.35 GHz. The roughness of the surface of the Oceans depends upon the wind velocity and this surface roughness in turn determines ε_ν and r_ν. Once these are known the brightness temperature can be calculated. In their early work they neglected the atmospheric contribution towards the brightness temperature. In view of this work we decided to check the atmospheric contribution over land and sea.

We calculated the brightness temperatures under identical conditions over land, whose emissivity was assumed to be 0.8, and over sea, whose emissivity is calculated to be 0.396. The results are shown in Table 3.1. For the ground temperature of 298 $^{\circ}$K the brightness temperature is 238.4 $^{\circ}$K on land and 119.2 $^{\circ}$K on the sea. For the same ground temperature, the land, therefore, emitts much more. The temperatures TB(I) are lower than εT_G due to attenuation in the atmosphere. The temperatures TB(II) are representing the atmospheric emission and are the same over land and sea for a particular frequency, since the atmospheric conditions were assumed to be identical. The temperature TB(III) is higher on sea than on land because the reflectivity of water is more than that of land. We next have a column for the net brightness temperature TB and finally a column for $(TB - \varepsilon T_G)$ which is the atmospheric contribution. We note that

at 22.235 GHz the atmospheric contribution is 22.46 ^{o}K over land and 75.09 ^{o}K over sea. For identical state of the atmosphere the contribution is much more over oceans than over land. This is also true at the off resonance frequency of 19.35 GHz, although as expected, the atmospheric contributions at this off resonance frequency are less than that at the resonance frequency.

We next considered the sensitivity of the brightness temperature to variations in various parameters. We considered a standard state with $T_0 = T_G = 298\ ^{o}K$, $\gamma = 6.5\ ^{o}K/km$, $K = 0.48\ km^{-1}$ and $W = 40\ Kg/mt^2$. We then found the variation necessary in each of the parameters, which by itself, will cause a brightness temperature change of 1 ^{o}K, which is the sensitivity of the radiometers on 'Bhaskar'. The results are tabulated in table 3.2.

It may be noted that a 1 ^{o}K change in the observed brightness temperature is caused by 1 - 2 ^{o}K change in the temperature of the surface. The surface temperatures can be accurately measured by surface stations on the land. This cannot be easily done on the sea. Next, the brightness temperature is rather sensitive to the emissivity and a change of about 0.005 can be detected.

The brightness temperatures are quite insensitive to the temperature lapse rate at 19.35 GHz. At the same frequency, they are also quite insensitive to variations in K and W on land. Finally they are quite insensitive to air temperatures near the surface at 19.35 GHz. The variation of emissivity of water with the wind velocity was calculated by Shifrin and Ionina(3). From these results we conclude as follows:

(i) Even at the non resonant frequency of 19.35 GHz the atmospheric contribution is considerable (29.82 ^{o}K) over oceans and it cannot be neglected. Over land it is less (9.6 ^{o}K), but not negligible.

(ii) The contribution of the atmosphere over land at 19.35 GHz is not only smaller but also relatively insensitive to the atmospheric parameters, in particular the total water content W. This smaller contribution can thus be estimated with even approximate values of parameters as obtained by the radiosonde measurements. These are available on land and generally not available on sea.

(iii) If polarization of the emission is not measured the change in emissivity with the change in wind speed from 0 - 30 mts/sec will cause a change of brightness temperature of only about 1 ^{o}K. This effect is very likely to be masked by the change of atmospheric parameters over oceans.

Therefore at the frequencies chosen, it is easier to study the land surface than the ocean surface.

The variation of brightness temperature with various parameters is shown in figs. 3.4 - 3.9. It may be noted that the dependence of brightness temperature on these parameters is linear or at the most quadratic.

It is therefore possible to write a linear algebraic expression for the TB in terms of the more sensitive parameters. As a preliminary result we find that we can fit approximately

by using the relation

$$TB = 0.866\ \varepsilon\ T_G + 1.301\ W - 4.876 \times 10^{-3}\ W^2 \qquad (3.4)$$

at 19.35 GHz. This expression needs to be improved by considering other possible terms in the expansion.

At 22.235 GHz, the sensitivity of TB upon K and γ increases apart from W, and therefore a relation similar to 3.4 needs more careful analysis. It was not possible to complete this analysis by the dead line of the submission of this thesis.

TABLE 3.1. Atmospheric contribution over land and sea.

ν (GHz)	ε	T_G (^oK)	εT_G (^oK)	TB(I) (^oK)	TB(II) (^oK)	TB(III) (^oK)	TB (^oK)	(TB-εT_G) (^oK)
22.235	0.8	298	238.4	182.07	66.22	12.56	260.86	22.46
	0.396	298	119.2	90.13	66.22	37.94	194.29	75.09
19.35	0.8	298	238.4	218.09	24.34	5.57	248.0	9.6
	0.396	298	119.2	107.95	24.34	16.83	149.12	29.82

TABLE 3.2. Sensitivity of TB on all parameters.

ν (GHz)	ε	TB (^oK)	T_G (^oK)	ε	γ ($^oK/km$)	K (km^{-1})	W (gms/mt^2)	T_o (^oK)
22.235	0.8	1	1.127	0.006	1.44	0.3	2.5	3.63
	0.396	1	1.521	0.006	1.07	0.1	0.74	2.82
19.35	0.8	1	1.23	0.004	6.34	0.23	4.6	11.97
	0.396	1	2.25	0.004	6.58	0.105	1.48	12.82

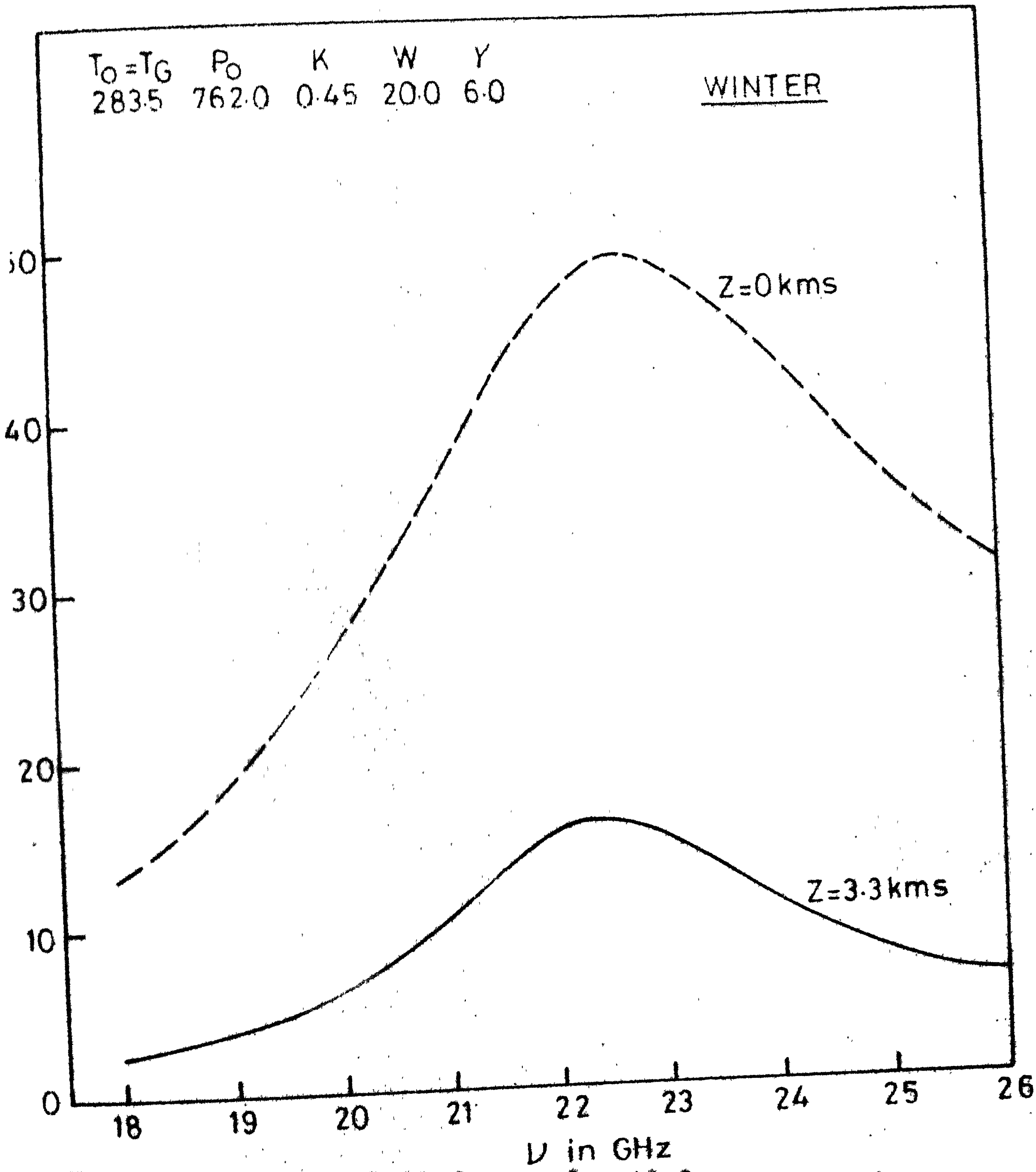


Fig. 3.1 . Alpha when plotted as a fn. of frequency, gives a resonance peak around 22 GHz . The assymetry is due to the non-resonant term contribution.

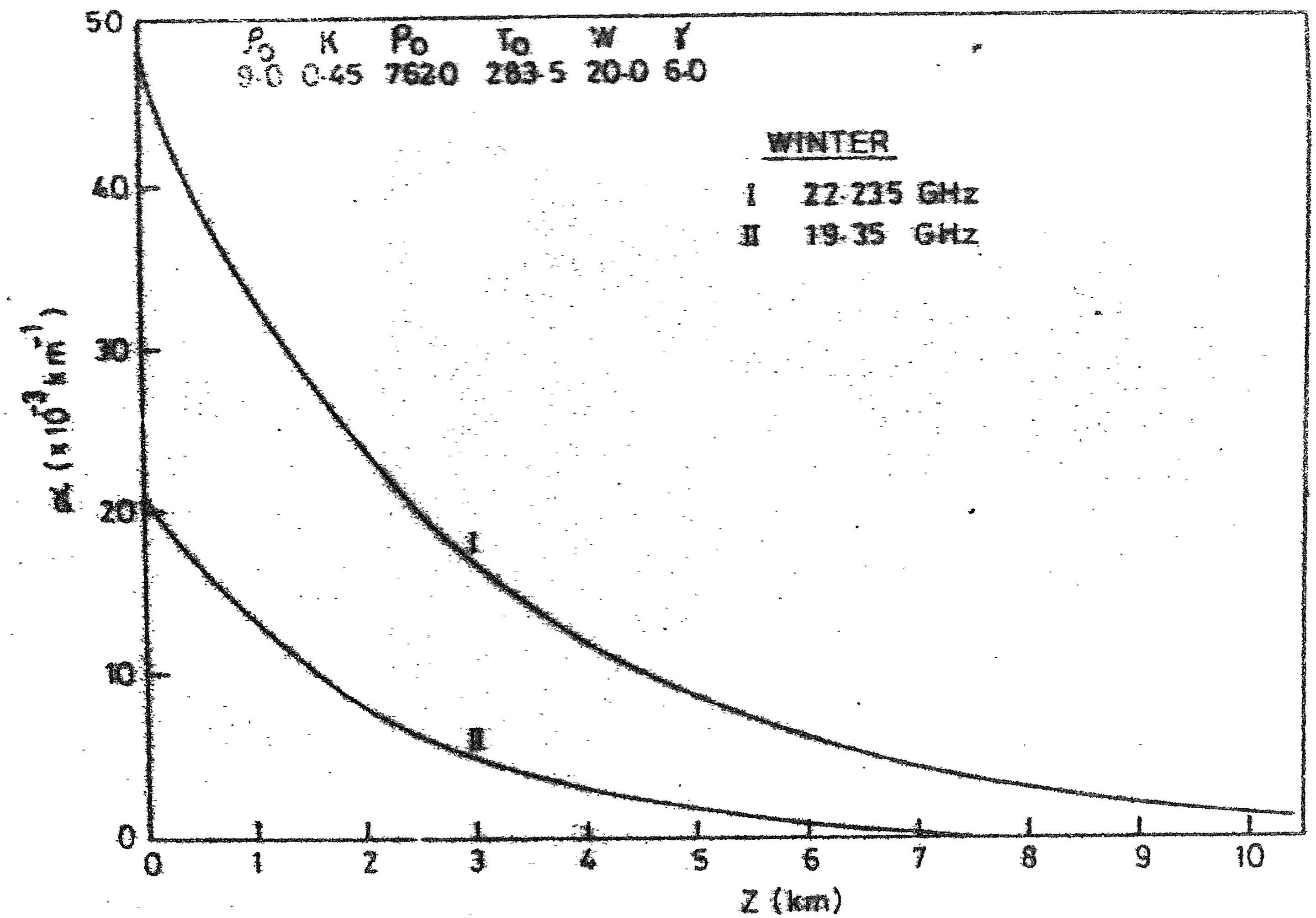


Fig. 3.2 The exponetial decay of Alpha with height plotted for the two frequencies 22-235 GHz and 19.35GHz.

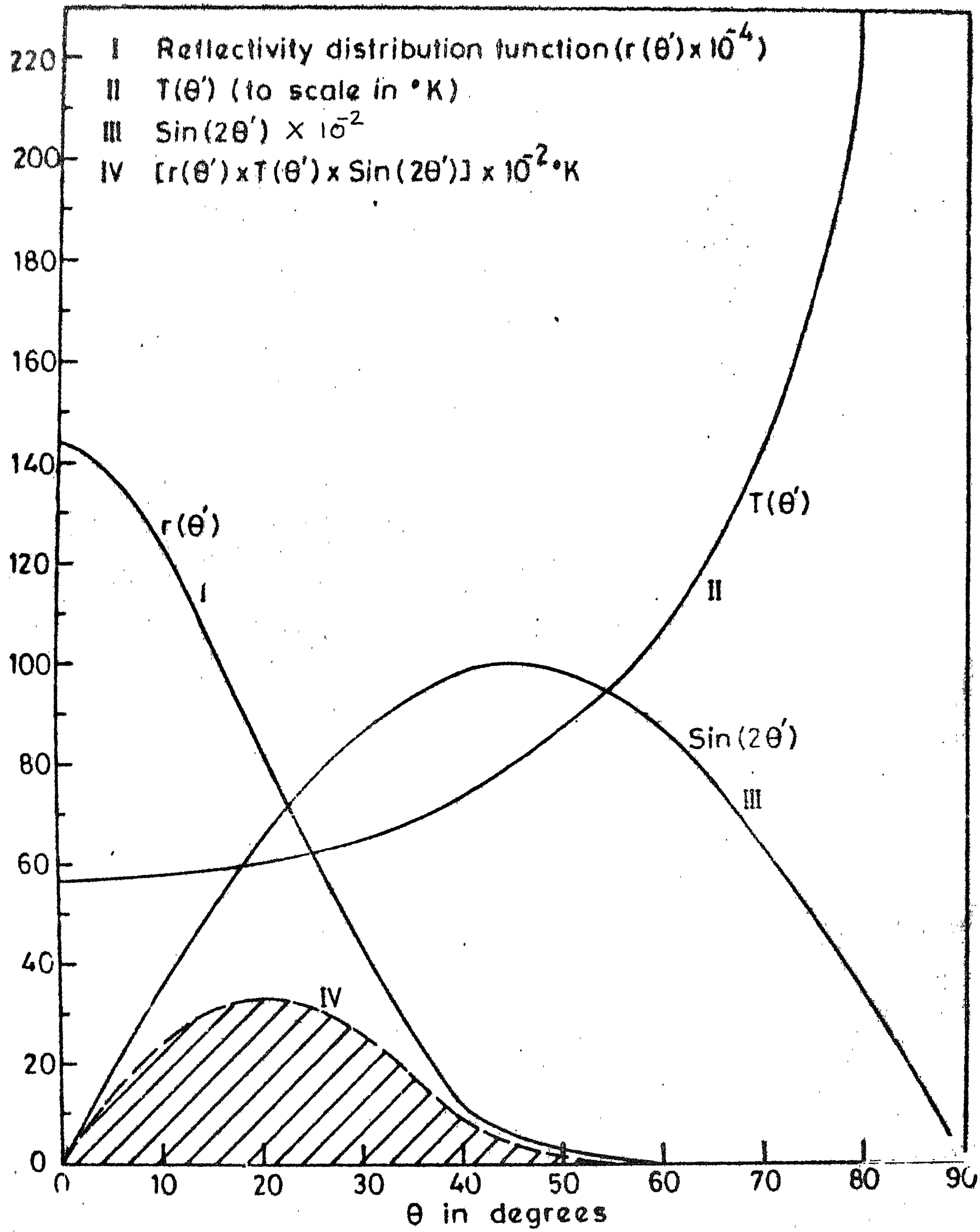


Fig. 3.3 Angular variation of parameters in T_B (III).

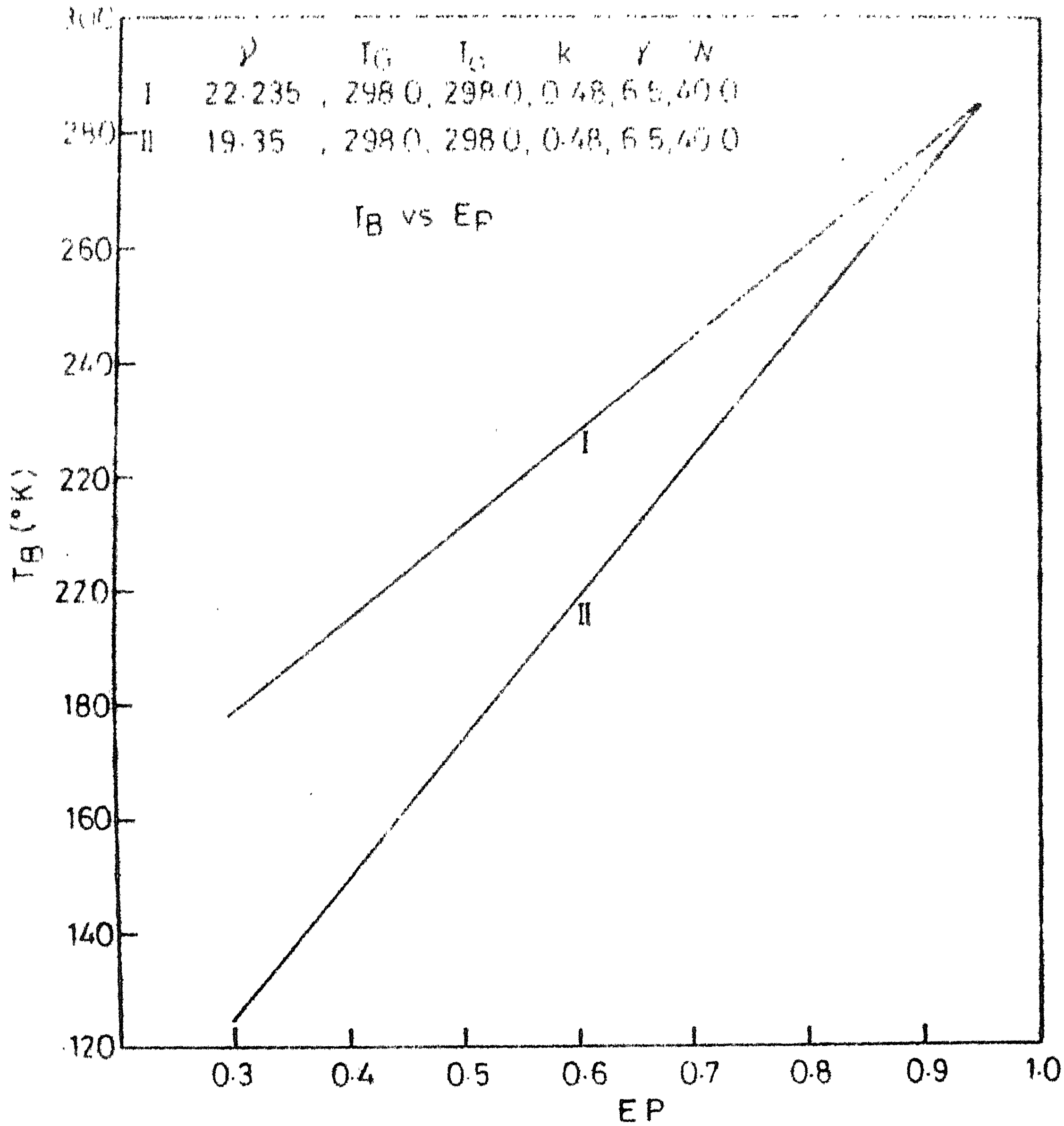


Fig. 3.4 Figures shows linear dependance of Brightness temperature TB upon EP the emissivity.

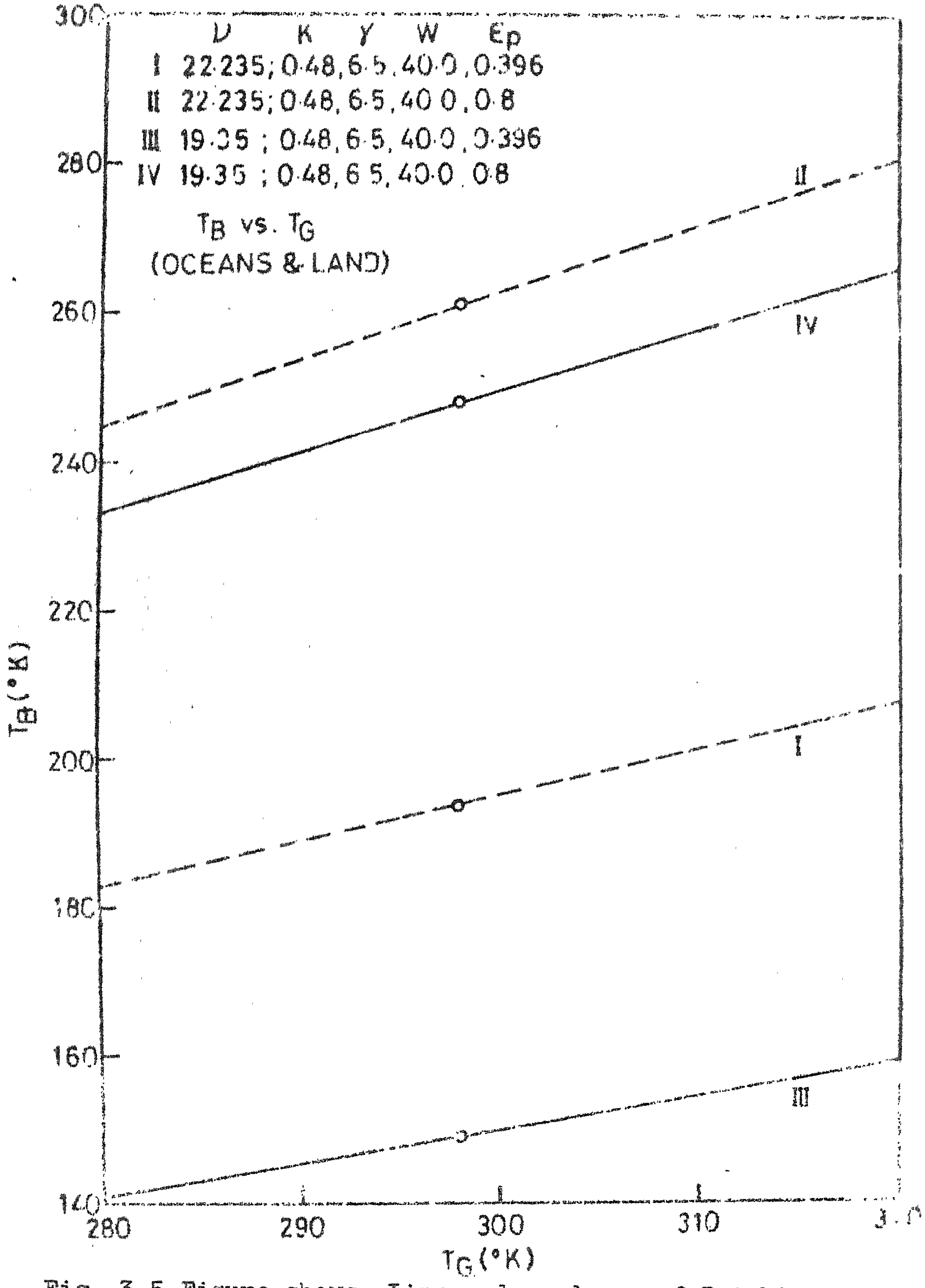


Fig. 3.5 Figure shows Linear dependence of Brightness temperature T_B upon TG, the ground temperature.

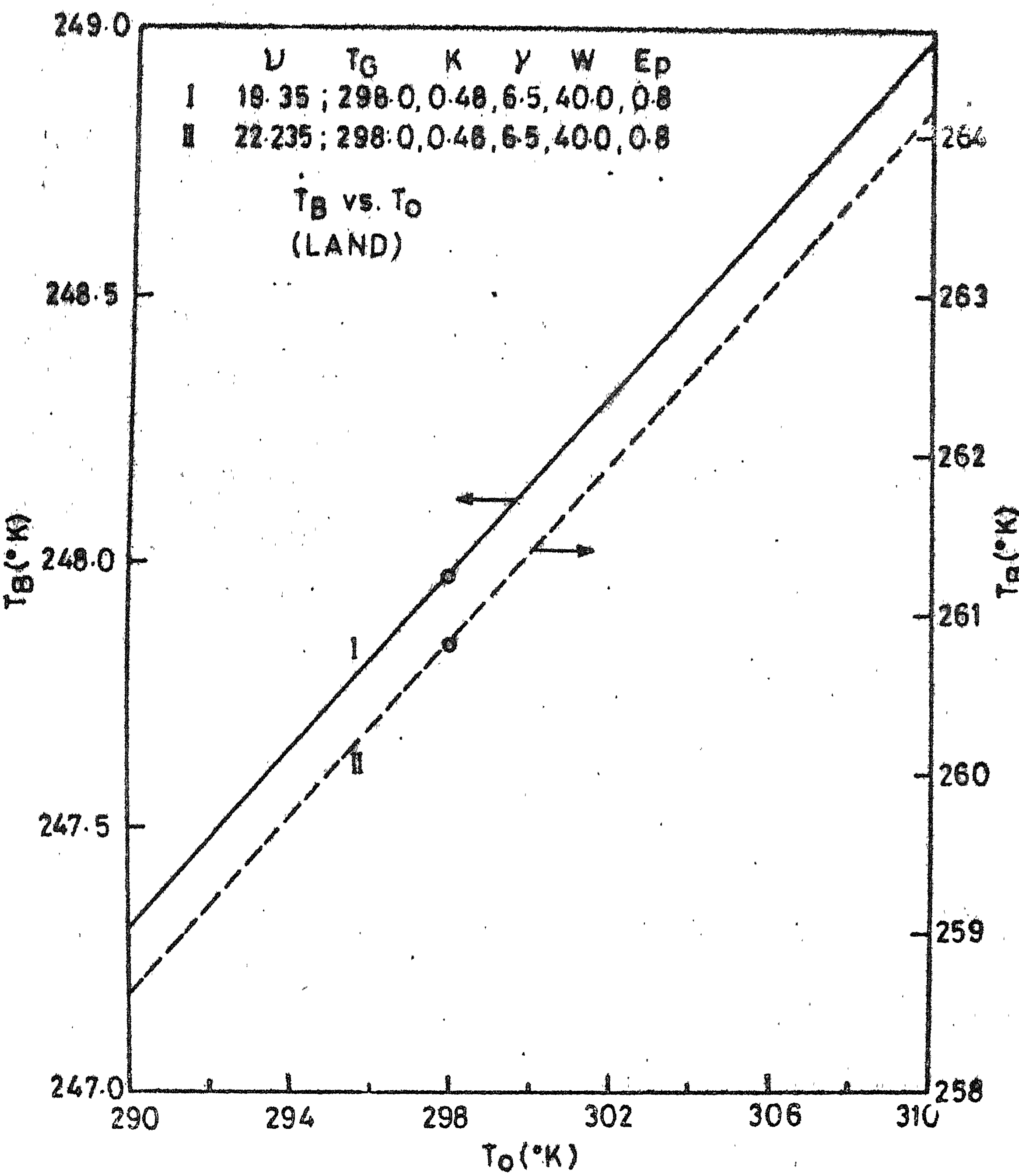


Fig. 3.6 (a) Figure shows linear dependence of the Brightness temperature TB upon TO, the earth's ground air temperature above land.

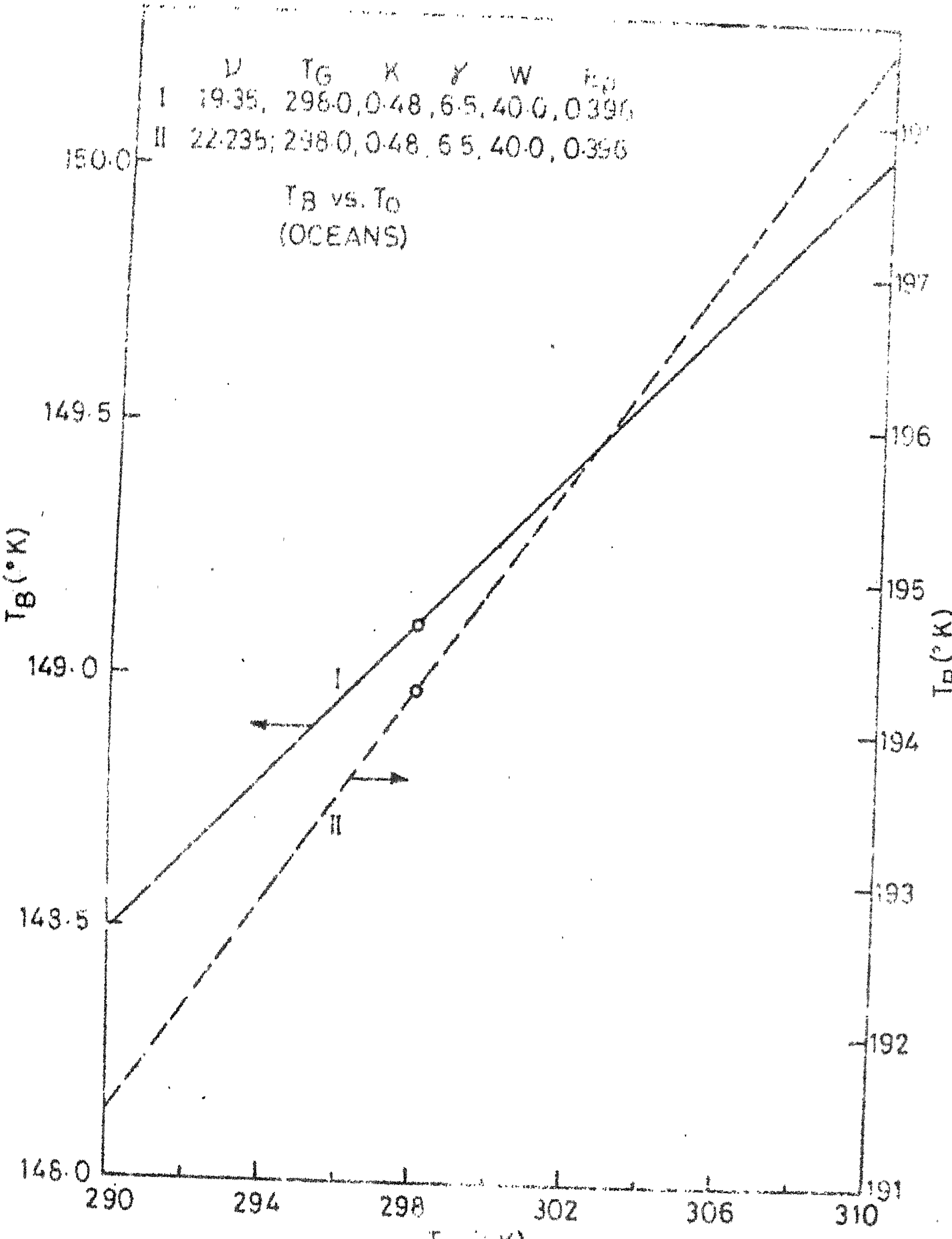


Fig. 3.6 (a) Figure shows linear dependence of the Brightness temperature TB upon TO, the earth's ground air temperature

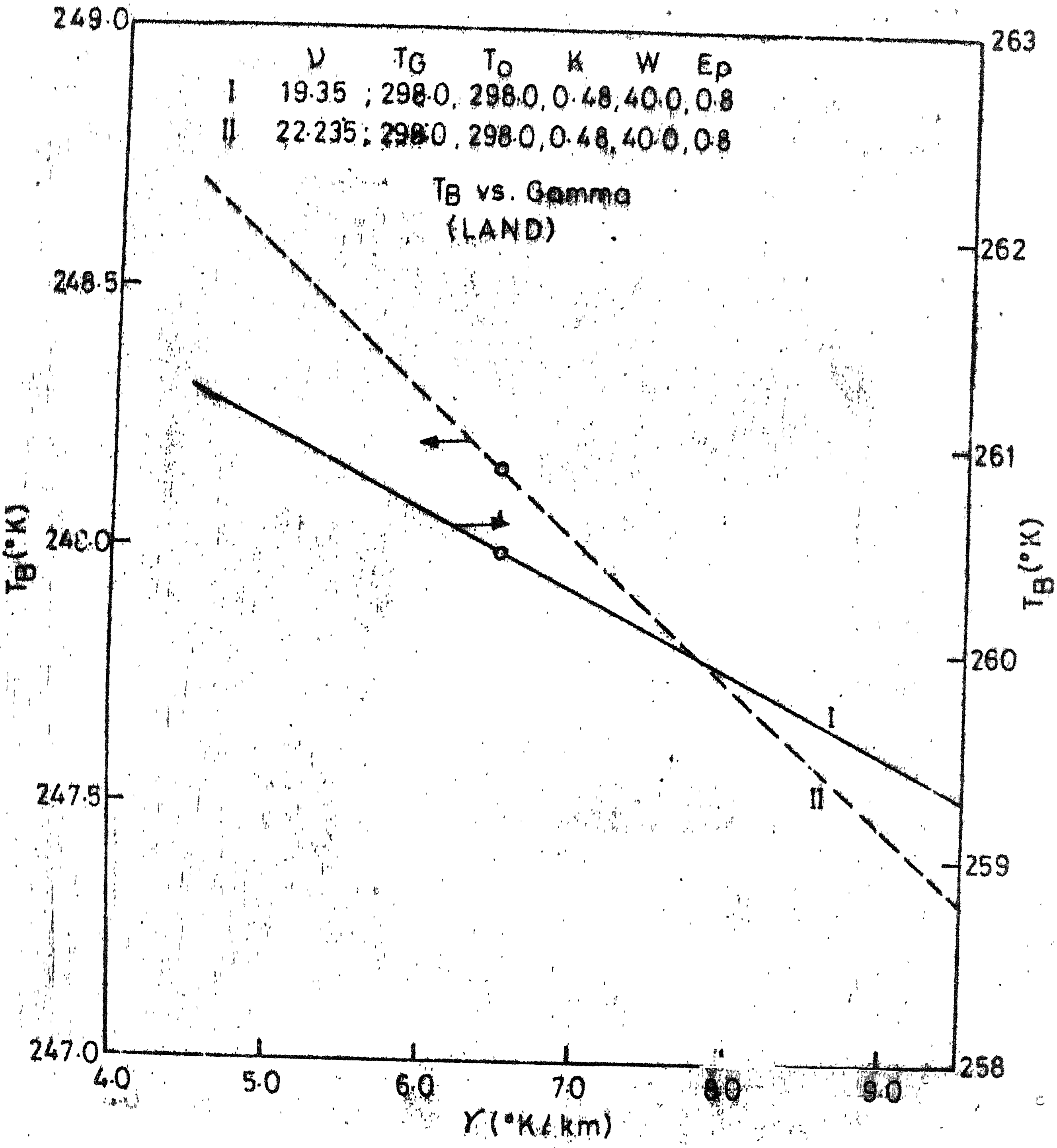


Fig. 3.7 (a) Figure shows linear dependence of Brightnesstemperatu ~~TxB~~ TB upon , the temperature lapse rate over land.

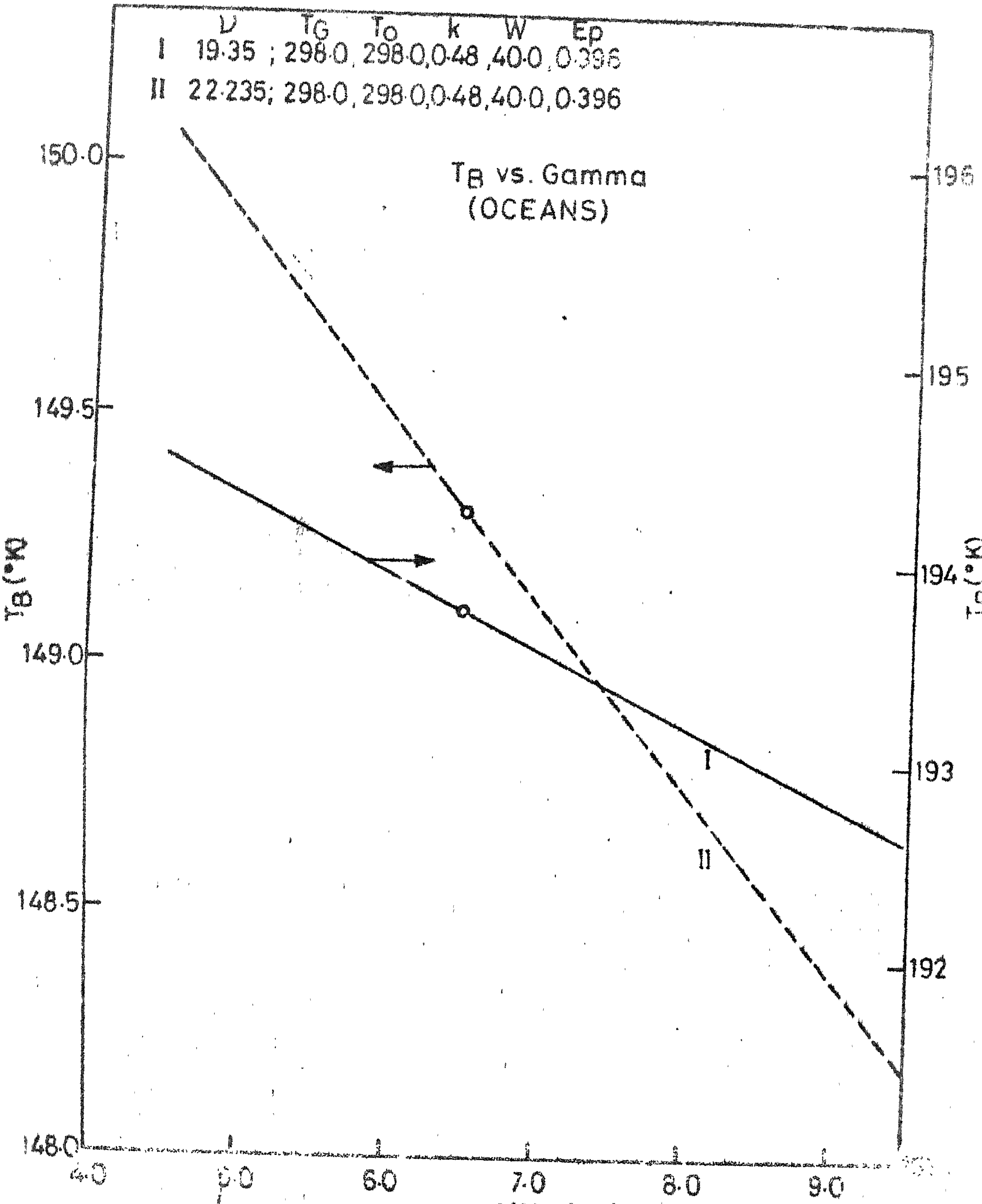


Fig. 3.7 (b) Figure shows **linear dependence brightness temperature TB upon, , the temperature laps rate over sea.**

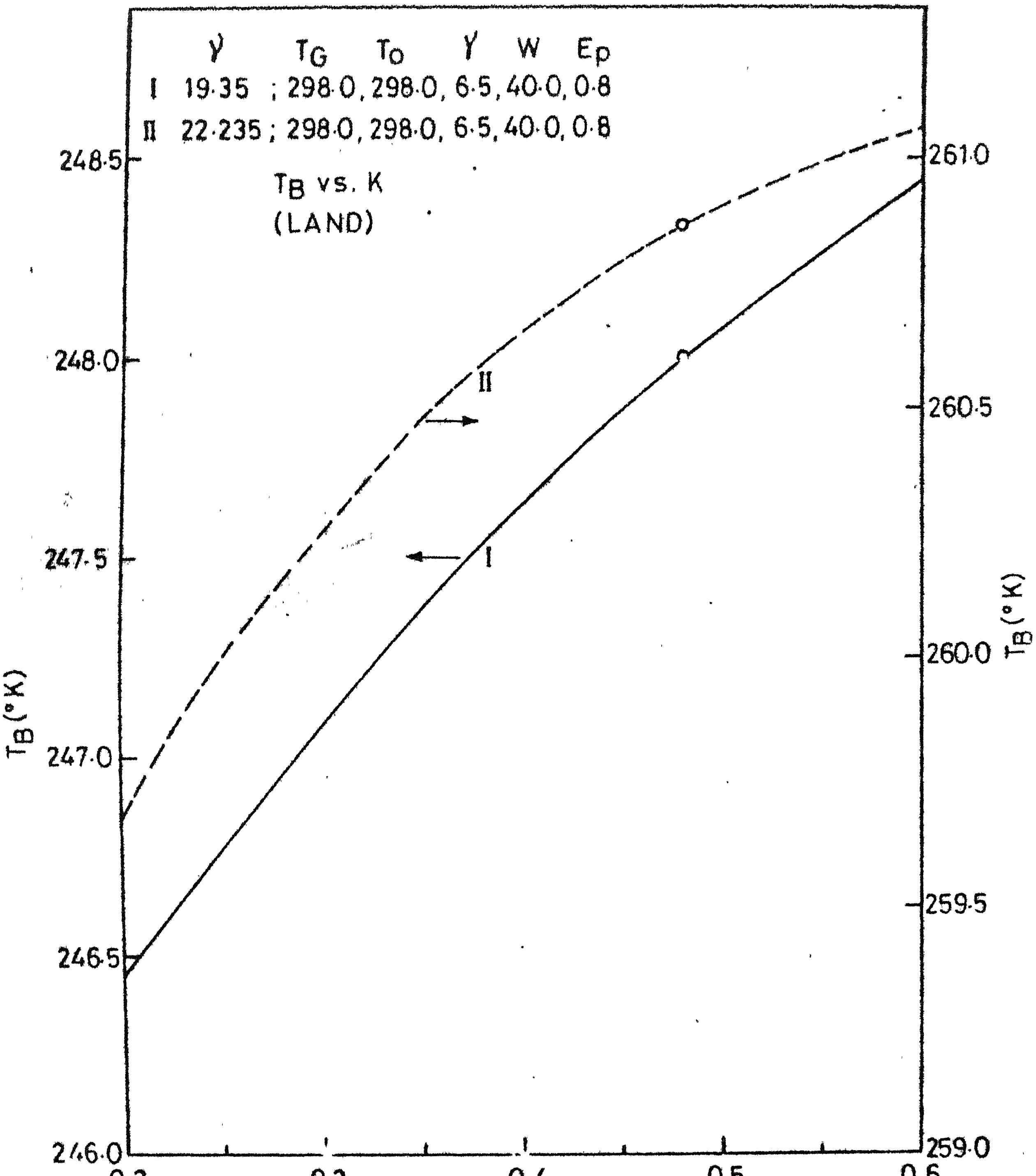


Fig. 3.8 (a) Figure shows quadratic dependence of Brightness temperature T^B upon K, the water vapour scale height over land.

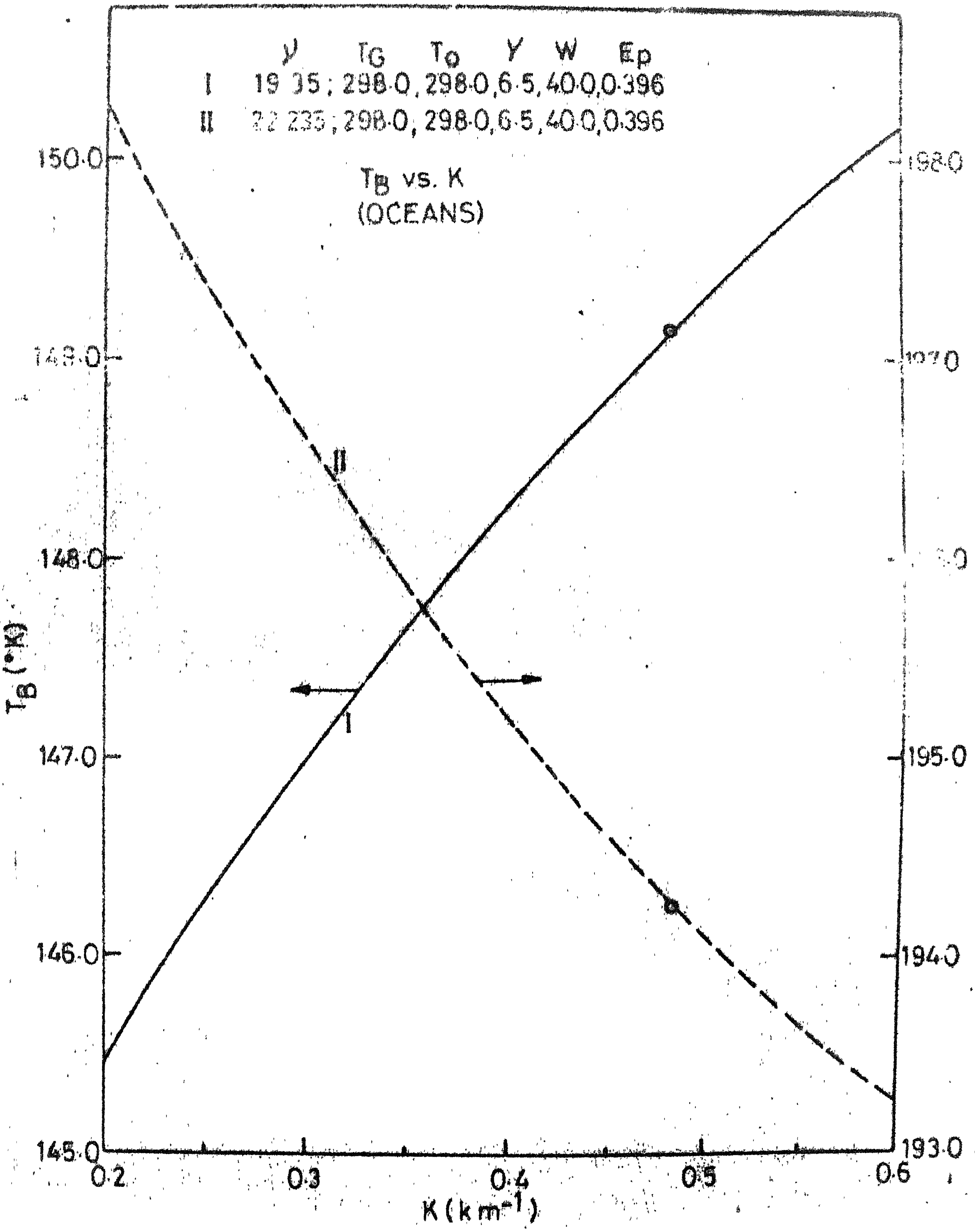


Fig. 3.8 (b) Figure shows quadratic dependence of brightness temperature TB upon K, the water vapour scale height over sea.

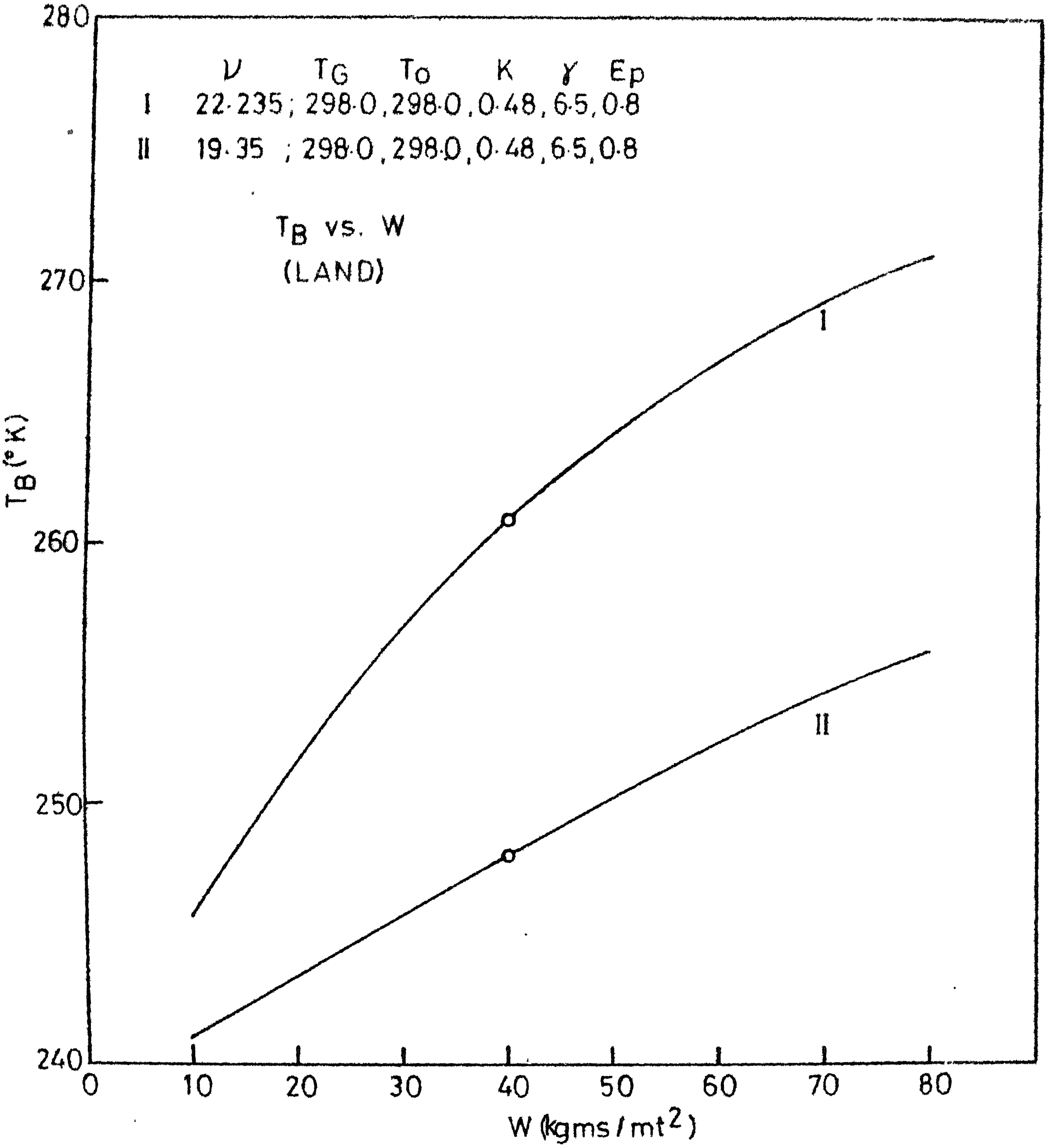


Fig. 3.9 Figure shows quadratic dependence of the brightness temperature TB upon W, the total water content of the atmosphere, over land.

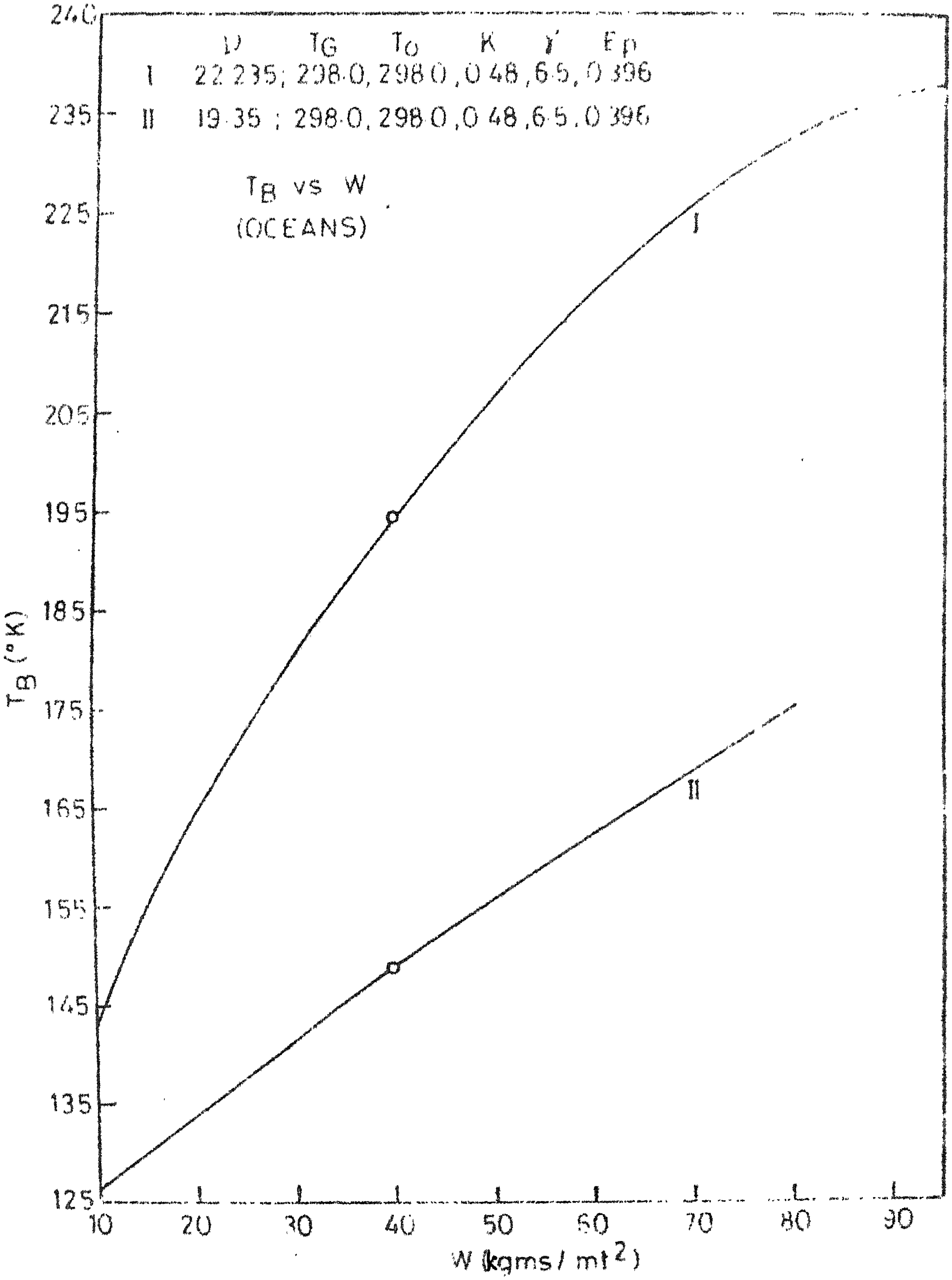


Fig. 3.9 (b) Figure shows quadratic dependence of the brightness temperature TB upon W, the total water content of the atmosphere over sea.

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